PEER REVIEWED

Milk Yield and Disease: Towards Optimizing Dairy Herd Health and Management Decisions

Y.T. Gröhn, *DVM, MPVM, PhD*
Section of Epidemiology
Department of Population Medicine and Diagnostic Sciences
College of Veterinary Medicine
Cornell University
Ithaca, NY 14853

Abstract

The purpose of our research is to develop a comprehensive economic model to assist dairy producers when making treatment and culling decisions. To make profitable decisions, the producer must account for factors including age, production level, stage of lactation, pregnancy status, and disease history. Establishing the interrelationships among disease, milk yield, reproduction, and herd management is necessary for developing a decision model for disease treatment, insemination, and replacement.

The objective of our research presented in this paper was to study the relationship between disease and milk production. First, we studied whether high milk yield predisposes a cow to certain diseases and reproductive disturbances. Second, we studied whether certain diseases cause milk loss and increased culling. Third, we are combining all information to develop a comprehensive economic model which will attempt to assess both the beneficial and deleterious effects of increasing milk yield.

The data for this study incorporate health, production, and management components for Holsteins in the Northeastern USA and Ayrshires from Finland. The data were analyzed using the Cornell Theory Center Supercomputer. The effect of milk yield was modeled with logistic regression, and conception and culling with a survival analysis technique. The effect of disease on milk yield was analyzed with mixed model analysis.

High milk yield predisposed a cow to certain diseases (particularly mastitis). Many diseases led to decreased production. Both milk yield and disease affected reproductive performance and culling. As expected, high milk yield protected against culling, and non-pregnant and sick cows were more likely to be culled. We now are positioned to develop a simple, accurate, and complete framework for a dairy farmer to determine whether a cow should be kept or replaced by a more profitable heifer using all of the biological variables that impact profitability in an objective manner.

Introduction

In recent years, milk yield has become much more dependent upon intensive methods of husbandry. Reduced profit margins and an increasingly competitive business environment for dairy producers have made veterinarians focus upon herd health and productivity. Incremental changes in milk yield can have major effects on profitability in this new business environment. Understanding the relationship between disease and milk yield is therefore of paramount importance for sustainability of the dairy industry. Our ultimate goal is to help farmers make the best decisions regarding management of their dairy herds. To do this we need first to understand the biological parameters involved, namely milk yield, disease, and reproductive performance.

Much debate has focused on whether the higher milk yield attained in recent decades has caused a concomitant increase in diseases of dairy cows. The effect of high milk yield on a cow's reproductive performance is also in question.[1,5,7,8,19,20] On the other hand, certain diseases would themselves decrease yield. However, these relationships have been difficult to demonstrate, and controversy exists in the literature. For example, there is a relationship between high milk yield and mastitis. Fortunately, few people would conclude that the purchase of mastitic cows will increase milk yield. The most plausible explanation is that cows with mastitis that have low yields are removed from the dairy herd, whereas high yielding cows are kept even if they had mastitis. Thus an association exists, but the cause and effect is not clear. Does high yield cause disease? Does disease decrease yield? These questions are clearly related, and difficult to understand merely by examining associations. An association could occur because some external factor (i.e., management) is affecting both yield and disease.

Although some studies regarding the relationship between disease and milk yield have been attempted, they have been constrained by three factors: lack of a large health data base; lack of computing power; and lack of sophisticated statistical tools. Fortunately, we have had access to high quality data on Finnish Ayrshires;[13,14,15] such data have not been previously available in the United States, where the Holstein breed predominates. More recently, we established a new health and production database in the Northeastern USA to study the association between milk yield and disease under Northeastern management methods.

There are three critical questions regarding the relationship between disease and production: Does high milk yield predispose a cow to: *i)* certain diseases and *ii)* delayed conception? The second question is: Does disease cause *i)* milk loss and *ii)* increased culling? Finally, I will discuss how the information can be combined so that the economic gains from increased yield can be compared to economic losses associated with increased disease occurrences. The material for this review was primarily taken from our own on-going epidemiologic (observational) research carried out with Holsteins in the Northeastern USA and with Ayrshires from Finland.

Studies on the Relationship Between Disease and Milk Production

The relationship of high milk yield to certain diseases

There has been much debate about whether high milk yield predisposes dairy cows to more diseases. These relationships have been difficult to demonstrate, as both biology and management contribute to milk production and disease. High milk yield may contribute to a negative energy balance in some cows, especially those still growing, and a diseased state may be created. Selective culling muddies the issue further. High yielding cows are more likely to remain in the herd, and receive more veterinary treatment, even when they become ill, than low producers.

To address this question, we conducted a study to examine whether the previous 305-d milk yield had any effect on 7 different disorders.[12] Logistic regression was used to study these associations in 8070 multiparous cows from 25 herds, calving between June 1990 and November 1993, in New York State. The 7 diseases (lactational incidence risk in parentheses) under study were retained placenta (7.4%), metritis (7.6%), ovarian cysts (9.1%), milk fever (1.6%), ketosis (4.6%), abomasal displacement (6.3%), and mastitis (9.7%). A separate logistic regression model was used for each disease. Parity, calving season, and herd (as a proxy of management) were included in each model as potential confounders (Table 1).

The diseases that did have a significant effect on outcome in each of the seven logistic regression models are shown in Table 1. The risk factors retained placenta and ketosis predisposed cows to metritis. Ketotic cows were 1.8 times and cows with retained placenta 6.2 times more likely to have metritis than those cows free of these disorders. Ketosis and mastitis raised the risk of ovarian cysts. Metritis, milk fever, and abomasal displacement raised the risk of ketosis. Retained placenta and ketosis were significant predictors of displaced abomasum. Ovarian cysts increased the risk of mastitis.

The highest milk yield was associated with a greater risk of only ovarian cysts and mastitis (Table 1). The highest yielding cows were most likely to have ovarian cysts, compared to the lowest yielding cows. The effect was more marked in mastitic cows. Cows with higher milk yield were more likely to develop mastitis; there was a linear relationship between milk yield and odds of developing mastitis.

In earlier studies on Finnish Ayrshires,[9,13,14,15,16] we found that high milk yield is associated with a number of disorders, such as metritis, ovarian cysts, and mastitis. In addition to breed difference, several other factors may account for the greater number of disorders associated with milk yield in Ayrshires than Holsteins. Finnish farms are much smaller than New York farms so management is likely to differ. The Finnish studies contained over 5 times as many cows as our New York study therefore smaller differences become significant. Also, in New York, a farmer may treat animals for disease, but in Finland only veterinarians treat animals.

The lack of association between milk yield and disease in the Holstein study, except for ovarian cysts and mastitis, may indicate that even the highest yielding cows can be managed to meet their biological needs. Our finding in Holsteins, that cows with higher milk yield were more likely to have ovarian cysts and mastitis, does not necessarily imply that higher milk yield, *per se*, causes ovarian cysts and mastitis. At least 2 biological explanations for the association between high milk yield and mastitis are plausible: increased risk of injury and leaking of milk between milkings. Management, a difficult factor to account for under the best of circumstances, almost certainly plays a role. Selective culling and selective treatment of cows may explain the association between high milk yield and occurrence of mastitis. Very high yielding cows, even when they become ill, are more likely to be kept in the milking herd for as long as possible; they are also more likely to receive treatment for

Table 1. Risk factors (cow milk yield, parity, calving season, and disease) for 7 diseases, each statistically modelled, in 8070 New York Holsteins. All 7 models included herd as a proxy of management.

	Diseases						
Risk Factors	Retained Placenta	Metritis	Ovarian Cysts	Milk Fever	Ketosis	LDA	Mastitis
Milk Yield, lb							
≤18,909	[1] 1.0	1.0	1.0	1.0	1.0	1.0	1.0
18,910-21,290	1.2	1.2	1.3	1.0	0.9	0.8	1.2
21,291- 23,420	1.3	1.1	1.2	1.1	1.1	0.9	1.3*
23,421-25,930	1.1	1.1	1.2	0.5	1.0	0.8	1.5*
>25,930	1.1	1.0	1.4*	0.8	1.0	0.8	1.6*
Parity							
2	1.0	1.0	1.0	1.0	1.0	1.0	1.0
>2	1.4*	1.2	1.0	3.7*	1.8*	1.6*	1.5*
Calving Season							
Sept-Nov	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Dec-Feb	1.0	1.3*	1.3*	1.5	1.0	1.2	1.4*
Mar-May	1.2*	1.5*	1.3*	1.2	1.7*	1.6*	1.2
June-Aug	1.2*	1.7*	1.1	1.1	1.6*	1.1	1.4*
Disease							
Retained Placenta	---	6.2*				2.2*	
Metritis		---			2.8*		
Ovarian Cysts			---				1.8*
Milk Fever				---	2.1*		
Ketosis		1.8*	1.6*		---	4.5*	
LDA					4.0*	---	
Mastitis			1.5*				---

[1] Values are odds ratios; an odds ratio is a measure of how much more likely the outcome is among observations with a given risk factor (or level of risk factor if >2 categories), compared with those without the risk factor (or reference category). A reference category (odds ratio = 1.0) for milk yield is <18,909 lb, for parity 2, for calving season between September and November and for each disease a cow without a particular disease.
*p<0.05

their ailments. Lower yielding cows will be culled sooner. The magnitude of the effect of selective culling needs to be addressed in future studies.

The relationship of milk yield to delayed conception

Reproductive performance in dairy cows can be influenced by many factors. Some factors are under the farmer's control, and some are not. Milk yield, in particular, may play an important role in reproduction. However, the relationship between milk yield and conception has been difficult to study because of the confounding effect of culling. Conception does not necessarily occur at the first breeding; cows may have to be inseminated several times. A cow that remains open (i.e., does not conceive) for an extended period of time or is a low milk producer is more likely to be culled. Some researchers have argued that high producing cows are less fertile than low producers. This association may, however, be complicated by selective culling.

The objective of this study was to measure the effect of 60-d cumulative milk yield on the rate of conception and rate of first breeding in lactation.[6] The data were from 15,320 New York Holsteins in 26 herds calving between June 1990 and November 1993. We used survival analysis, a statistical technique that allows inclusion of information on all cows, whether or not they had conceived or had been bred by the end of the study. Thus, the loss of valuable information was minimized.

Parity, calving season, and herd as a proxy of management were included in the analysis as confounders.

Retained placenta, metritis, and ovarian cysts were significant risk factors for conception (Table 2). Cows with retained placenta, metritis, or cystic ovary, had 14, 15, and 21% lower conception rates, respectively, than those free of these disorders. Metritis, ovarian cysts, and mastitis were associated with reduced rates of insemination (Table 3).

We found that current cumulative 60-d milk yield has no effect on conception rates (Table 2). The highest yielding cows had a slightly lower (but not significant) conception rate than did the lowest yielding cows. However, 60-d milk yield did have an effect on the likelihood that a cow would be inseminated (Table 3). As milk yield increased, so did insemination rates. The highest producers were nearly 30% more likely to be inseminated than were the lowest producing cows.

Table 2. Effect of milk yield, parity, calving season, and disease on conception in 13,307 New York Holsteins.

Risk Factor	Hazard Ratio[1]
First 60-d Cumulative Milk Yield, lb	
≤3,480	1.0
3,481-4,160	0.99
4,161-4,830	1.01
4,831-5,590	1.01
>5,590	0.92
Parity	
1	1.0
2	0.98
≥3	0.92**
Calving Season	
December-February	1.0
March-May	0.93*
June-August	1.06
September-November	1.01
Disease	
Retained Placenta	0.86**
Metritis	0.85**
Ovarian Cysts	0.79**

[1]Hazard ratios for factors in proportional hazards model. The term hazard ratio refers to the ratio between two relative risks of an event (e.g., conception). For example, if a cow has a hazard ratio of 0.92 (parity ≥3), this means that a cow has an 8% reduced likelihood of conceiving than a first parity cow.
*p<0.05 **p<0.01

Among 30,036 multiparous Finnish Ayrshire cows the lowest producers were significantly less likely to conceive than were average producers.[17] Among 11,761 heifers, the highest producers were significantly less likely to conceive than were average producing heifers. Anestrus, ovulatory dysfunction, other infertility, late metritis, and clinical ketosis played a role in decreasing conception probability[18] among 30,036 multiparous and 11,761 primiparous cows.

The results of this study on New York Holsteins indicate that first 60-d milk yield has only a minimal effect on conception. Only the highest producers had a slightly lower conception rate than their herdmates. Older cows and cows with diseases were less likely to conceive. In contrast, the rate of being bred increased with 60-d milk. These latter two findings appear to demonstrate that producers are mak-

Table 3. Effect of milk yield, parity, calving season, and disease on likelihood of being bred for the first time in lactation in 15,320 New York Holsteins.

Risk Factor	Hazard Ratio[1]
60-d Cumulative Milk Yield, lb	
≤3,140	1.0
3,411-4,120	1.11**
4,121-4,790	1.11**
4,791-5,560	1.17***
>5,560	1.29***
Parity	
1	1.0
2	0.96
≥3	0.77***
Calving Season	
December-February	1.0
March-May	0.94*
June-August	1.13***
September-November	1.08**
Disease	
Metritis	0.87**
Ovarian Cysts	0.39***
Mastitis	0.71***

[1] Hazard ratios for factors in proportional hazards model. The term hazard ratio refers to the ratio between two relative risks of an event (e.g., first breeding). For example, if a cow has a hazard ratio of 0.77 (parity ≥3), this means that a cow has a 23% reduced likelihood of being bred than a cow in parity 1.
*p≤0.05 **p≤0.01 ***p≤0.0001

ing rational decisions by breeding young, healthy, high yielding cows.

Management almost certainly plays a role in these findings. High producing cows, even if they have trouble conceiving or are ill, will be given more opportunity and are more likely to remain in the herd than low producers.

The relationship of disease and milk loss

It seems obvious that disease causes milk loss, but surprisingly, some studies have actually found that increased milk yield is associated with disease. The way in which milk yield is expressed in the analysis is very important; a single summary measure of milk yield (e.g., 305 day yield) may give a completely different answer than monthly milk yields.[4]

The objective of this study[3] was to evaluate the direct causal effects of left displaced abomasum on test day milk yields taken approximately once a month on 12,572 New York Holsteins. A linear model, containing both fixed and random effects, was fitted for each parity separately. We found that cows with left displaced abomasum (LDA) produced significantly less milk than did cows without LDA (Table 4).

In our earlier study of ketosis,[4] involving 60,851 Finnish Ayrshires, we found that ketotic cows, although yielding less milk during the episode of ketosis than nonketotic cows, actually yielded more milk over the entire lactation than did nonketotic cows.

In a recent, more comprehensive study,[21,25,26] involving 39,727 Finnish Ayrshires, we found that daily milk losses due to clinical mastitis, ketosis, milk fever and lameness varied between 2.2 and 11.7 lb, depending on the disease. Milk production began to decline by two to four weeks before the diagnosis of ketosis, mastitis and lameness, suggesting a presence of subclinical disease. Despite this loss, cows with milk fever, ketosis, and mastitis produced more milk during the whole lactation than their healthy herdmates. Dystocia, retained placenta, and early metritis were associated with reduced milk production.

It seems very likely that there will always be some loss of milk yield after disease. It is very important to use proper methodology when attempting to quantify the loss, i.e., it is more accurate to use monthly measurements of milk yield rather than a single, summary lactational measure. Only in this way can true losses be observed. Accurate measurement of milk yield loss following disease and knowing whether the milk loss is temporary or sustained, is important and will help a farmer decide whether it is worth keeping the cow in the milking herd.

The relationship of disease and culling rate

Culling is a complex issue, and many factors are involved. Dairy cows may be culled for either involuntary reasons (i.e., death, acute disease, infertility) or voluntary reasons (i.e., low production). Both biology and management affect the decision to cull. When making a decision, the dairy farmer considers at least five major reasons: illness, milk yield, conception status, stage of lactation, and parity. A further complication in culling studies has been the fact that diseases may have different effects on the decision to cull depending on when they occur or when their effects are observed. Therefore, erroneous conclusions may be drawn if dis-

Table 4. Summary of results in New York Holsteins and Finnish Ayrshires on a significant effect of disease on test-day milk yields (values are estimates of average milk loss (lb) by parity).

Disease	**Parity**					
	1	2	3	4	5	6
Ketosis[a] (Detilleux et al., 1994)	74.6	97.5	103.6	115.7	80.1	114.0
LDA[b] (Detilleux et al., 1997)	—	1007.8	845.9	1034.7	471.0	—
Milk Fever (Rajala et al., 1999d)	—	83.2	175.6	73.9[c]		
Dystocia (Rajala et al., 1998)	—	67.8	—	—		
Retained Placenta (Rajala et al., 1998)	385.7	89.3	—	—		
Metritis (Rajala et al., 1998)	43.1	40.0	129.4			
Ketosis (Rajala et al., 1999d)	277.2	277.2	147.8	1177.9[c]		
Lameness (Rajala et al., 1999d)	683.1	—	67.8	304.9[c]		
Mastitis (before peak) (Rajala et al., 1999e)	646.8	624.8	1119.8	1214.4[c]		
Mastitis (peak - 120 d) (Rajala et al., 1999e)	765.6	660.0	774.4	723.8[c]		
Mastitis (after 120d) (Rajala et al., 1999e)	220.0	484.0	631.4	785.4[c]		

[a]Losses pertain to the 17 d following diagnosis.
[b]Losses pertain to the 60 d following diagnosis.
[c]Parity 4+

eases are considered to have only one effect (i.e., at only one point in time) on culling. Only a few studies have incorporated the dependence on time because the statistical techniques available were not yet capable of assessing time-dependent explanatory variables in the model. We have described the methodological aspects involved in the estimation of the time-dependent effect of disease on culling.[10]

Using this approach (survival analysis with time dependent covariates), we studied the effect of seven diseases on culling. The modifying effects of milk yield and conception status on whether diseases resulted in culling were also studied, and the interactions between these covariates and stage of lactation were taken into account.[11] The data consisted of 7523 New York Holsteins in 14 herds; they calved between January 1, 1994 and December 31, 1994 and were followed until September 30, 1995.

The effects of parity and conception status on culling are given in Table 5. The data are expressed as risk ratios which measure the risk of a cow being culled due to a particular factor compared with a reference level (1.0 - not having that factor). Older cows were at higher risk of culling, as were cows that had not yet conceived. For instance, cows in parity 6+ were 4.7 times more likely to be culled than cows in parity 1; similarly, open cows (i.e., before conception) were 7.5 times more likely to be culled than pregnant cows. Results indicated that high milk yield is protective against culling, except in early lactation (Table 6).

Several disorders had an effect on culling. The reference was a cow without the disease; only significant results are presented in Table 7. Diseases that increased risk of culling included milk fever, LDA, and ketosis. Mastitis, in particular, had a significant detrimental effect on culling, i.e., cows with mastitis were more likely to be culled than were those without. The effect varied both with time of occurrence of mastitis and time of culling. Ovarian cysts had no effect on culling when conception status was included in the model. However, when conception status was not included in the model, cows with ovarian cysts were 1.9 times more likely to be culled in late lactation. This implies that the effect of ovarian cysts is partially explained by conception status. Therefore, ovarian cysts were not significant when conception status was included in the model. As expected, when milk yield was high, culling was less likely and when disease was present, culling increased. Common sense dictates this conclusion, as do the results of our previous studies. We have recently confirmed these findings on Holsteins agreeing with Finnish Ayrshires.[11,22,23,24]

Table 5. Effects of parity and conception status on culling.

Parity	Risk Ratio[1]
1	1.0
2	1.8***
3	2.8***
4	3.3***
5	4.2***
6+	4.7***
Before conception	7.5***
After conception	1.0

[1]Risk ratios measure the risk of being culled for a cow with a particular factor compared with a reference level (1.0).
***p<0.001

Table 6. Effects of milk yield on culling. Values are risk ratios.[1]

	Stage of lactation when culled					
Milk Yield Level	1-30 d	31-60 d	61-120 d	121-180 d	181-240 d	>240 d
Heifers	1.7**	. . .				
Missing[2]	0.4	. . .	40***	12***	7.2***	7.4***
1 (lowest)	1.2	22***	7.1***	4.1***	7.2***	4.3***
2	0.9	2.6	1.2	1.5	1.8*	1.5**
3	1.0	1.0	1.0	1.0	1.0	1.0
4	0.8	1.9	1.2	0.8	0.8	0.8
5 (highest)	1.1	1.5	0.8	0.5*	0.6	0.5***

[1]Risk ratios measure the risk of being culled for a cow with a particular factor compared with a reference level (1.0).
[2]"Missing" represents cows (likely diseased; fewer than 40 out of 7523) that were missing milk yield measurement but that were known to be in the milking herd at the time.
*p<0.05 **p<0.01 ***p<0.001

Table 7. Effect of milk fever, LDA, ketosis and mastitis on culling (only significant results shown). Values are risk ratios.[1]

	Stage of lactation when culled				
Time of Disease	1-30 d	61-120 d	121-180 d	181-240 d	>240 d
Milk fever					
1-30 d	2.3*				2.1*
LDA					
1 - 30 d	2.3***				
Ketosis					
1- 30 d	1.9**		1.7*		1.6**
Mastitis					
1-30 d	1.9***				
1-60 d		2.5***	2.2***	1.7*	
61-150 d		6.5***	3.0***	2.0*	
151-270 d				3.6***	
>270 d					2.7***

[1]Risk ratios measure the risk of being culled for a cow with a particular factor compared with a reference level (1.0).
*p<0.05 **p<0.01 ***p<0.001

Economic modeling

All of these studies have been done to achieve our long-range goal, which is to develop a simple computer program to assist veterinarians and dairy farmers in making management decisions concerning their cattle. Treatment and culling decisions represent an area of dairy herd management that affects profitability. To make rational decisions, the producer must have a valid estimate of the future profitability of each cow, accounting for factors including age, current production level, stage of lactation, pregnancy status, and disease history. Rational decisions are based on all of these factors when selecting cows to be treated or culled.

When using biological parameters in economic modeling of dairy management decisions, cows must be described mathematically. This allows estimation of economic effects of disease through decreased production, increased treatment costs, and risk of death. The usual framework for dynamic programming models is to use "state" variables to describe a cow.[2] At any stage of the cow's life, she is considered to be in a unique state which is described by values of the state variables. A state is defined by parity, month of conception, month of lactation, within herd milk production level, month of calving, and disease. Transition probabilities describe the likelihood of changing from one state to another. These are obtained through work, such as that described above (measuring biological parameters, such as milk yield, disease, and reproductive performance). The probabilities are then entered into the dynamic programming model, and the net present value of the cow is obtained. This is the objective of our current research - to help the producer determine whether a cow should be kept or replaced by a more profitable heifer using all of the biological variables that impact on profitability in an accurate and objective manner.

Discussion

To appreciate the complexity involved in measuring the associations discussed in this presentation, one must realize the limits of epidemiological research. The major difficulty is that what is observed is the product of both biology (within cow factors, such as genetics, milk yield potential, and disease history) and environment (herd factors, such as housing, feeding, and other management decisions). The main biological issue is whether milk yield is so important that it has been pushed to the point that it causes disease, or whether milk yield decreases before clinical disease occurs. It seems reasonable to assume that cow performance is regulated by available nutrients. Selection bias also plays a role in the findings; cows are managed and culled selectively. Nevertheless, with the proper study design and the control of confounding factors, such as parity, calving season, and herd, valid and largely objective estimates can be obtained.

In New York Holsteins, we found high milk yield to be a risk factor for ovarian cysts and mastitis, but not for any other disorders. High milk yield had no effect on conception rate, but it did increase a cow's chance of being inseminated. We also found that diseases, such as LDA, can cause short-term milk losses. High milk yield is protective against culling, and a number of disorders, including milk fever, LDA, ketosis, and mastitis, increase the chance of culling.

Results of our studies on New York Holsteins agree, in general, with our previous and current work with Finnish Ayrshires. Some differences occur that may be due in part to the larger sample size and more accurate disease recording in Finland. In New York, disease recording is still quite incomplete and variable in some areas, although it is constantly improving. Consequently, many diseases may be underreported in New York. It seems likely that most disorders would occur at roughly the same frequency in both populations, although variations in management likely influence disease occurrence to a certain extent. For instance, Finnish farms are much smaller than New York farms, and different feeding strategies exist. In addition, reproductive and culling policies may differ between the two populations.

Thus, we have seen that milk yield and various disorders are closely interrelated; milk yield appears to play only a minor role. High milk yield may predispose a cow to a particular disorder(s), and many disorders may be responsible for a drop (albeit sometimes temporary) in production. Both milk yield and disease may also play a role in reproductive performance. In addition, all of these factors are associated with culling. High milk yield is protective against culling, even in the presence of disease. Poor reproductive performance and/or slow recovery from disease may increase the risk of culling.

Having quantified all of these biological parameters, we are incorporating them in an economical model to help producers make decisions that will maximize their profitability. The end result of a dynamic programming approach is the net present value of a cow; this can be compared to that of another potential replacement. Thus, producers will have the necessary information needed to make rational decisions to enhance profitability of their dairy herds.

Acknowledgments

The initial work of this project was the AVMA Foundation Research Proposal "The effect of high milk production on disease and reproduction in dairy cows: logistic and survival analysis", 1991-1992. The major funding for the project was provided by the USDA National Research Initiative Competitive Grants Program (award number 92-03884), 1992-1995 and (award number 94-02316), 1994-1997. The current research on optimizing and delivering dairy herd health and management decisions is funded by the USDA Rural Fund of America (award number 97-05048), 1998-2000, and the USDA National Research Initiative Competitive Grants Program (award number 98-02405), 1998-2001. This research was conducted using the resources of the Cornell Theory Center (Cornell University, Ithaca, NY), which received major funding from the National Science Foundation (Arlington, VA), and New York State with additional support from the Advanced Research Projects (Arlington, VA), the National Center for Research Resources at the National Institute of Health (Bethesda, MD), IBM Corporation (Armonk, NY), and other members of the center's Corporate Partnership Program.

References

1. Butler WR, Smith RD: Interrelationships between energy balance and postpartum reproductive functions in dairy cattle. J Dairy Sci 72:767-783, 1989.
2. DeLorenzo MA, Spreen TH, Bryan G R, Beede DK, van Arendonk JAM: Optimizing model: insemination, replacement, seasonal production, and cash flow. J Dairy Sci 75:885-896, 1992.
3. Detilleux JC, Gröhn YT, Eicker SW, Quaas RL: Effects of left displaced abomasum on test day milk yields of Holstein cows. J Dairy Sci 80:121-126, 1997.
4. Detilleux JC, Gröhn YT, Quaas RL: Effects of clinical ketosis on test day milk yields in Finnish Ayrshire cattle. J Dairy Sci 77:3316-3323, 1994.
5. Dohoo IR, Martin S: Disease, production and culling in Holstein-Friesian cows. III. Disease and production as determinant of disease. Prev Vet Med 2:671-690, 1984.
6. Eicker SW, Gröhn YT, Hertl JA: The association between cumulative milk yield, days open, and days to first breeding in New York Holstein cows. J Dairy Sci 79:235-241, 1996.
7. Erb HN: Interrelationships among production and clinical disease in dairy cattle: a review. Can Vet J 28:326-329, 1987.
8. Farin PW, Slenning BD, Correa MT, Britt JH: Effects of calving season and milk yield on pregnancy risk and income in North Carolina Holstein cows. J Dairy Sci 77:1848-1855, 1994.
9. Gröhn YT, Bruss ML: Effect of diseases, production, and season on traumatic reticuloperitonitis and ruminal acidosis in dairy cattle. J Dairy Sci 73:2355-2363, 1990.
10. Gröhn YT, Ducrocq V, Hertl JA: Modeling the effect of a disease on culling: an illustration of the use of time dependent covariates in survival analysis. J Dairy Sci 80:1755-1766, 1997.
11. Gröhn YT, Eicker SW, Ducrocq V, Hertl JA: The effect of diseases on the culling in New York State Holstein dairy cows. J Dairy Sci 81: 966-978, 1998.
12. Gröhn YT, Eicker SW, Hertl JA: The association between previous 305-day milk yield and disease in New York State dairy cows. J Dairy Sci 78:1693-1702, 1995.
13. Gröhn YT, Erb HN, McCulloch CE, Saloniemi HS: Epidemiology of metabolic disorders in dairy cattle: association among host characteristics, disease, and production. J Dairy Sci 72:1876-1885, 1989.
14. Gröhn YT, Erb HN, McCulloch CE, Saloniemi HS: Epidemiology of reproductive disorders in dairy cattle: associations among host characteristics, disease and production. Prev Vet Med 8:25-39, 1990a.
15. Gröhn YT, Erb HN, McCulloch CE, Saloniemi HS: Epidemiology of mammary gland disorders in multiparous Finnish Ayrshire cows. Prev Vet Med 8:241-252, 1990b.
16. Gröhn YT, Hertl JA, Harman JL: Effect of early lactation milk yield on reproductive disorders in dairy cows. Am J Vet Res 55:1521-1528, 1994.
17. Harman JL, Gröhn YT, Erb HN, Casella G: Event-time analysis of the effect of 60-day milk production on the parturition-to-conception interval in dairy cows. Am J Vet Res 57:634-639, 1996a.
18. Harman JL, Gröhn YT, Erb HN, Casella G: Event-time analysis of the effect of season of parturition, parity, and concurrent disease on parturition-to-conception interval in dairy cows. Am J Vet Res 57:640-645, 1996b.

19. Marti CF, Funk DA: Relationship between production and days open at different levels of herd production. J Dairy Sci 77:1682-1690, 1994.
20. Nebel RL, McGilliard ML: Interactions of high milk yield and reproductive performance in dairy cows. J Dairy Sci 76:3257-3268, 1993.
21. Rajala PJ, Gröhn YT: Effect of dystocia, retained placenta, and metritis on milk yield in Finnish Ayrshire cows. J Dairy Sci 81: 3172-3181, 1998.
22. Rajala PJ, Gröhn YT: Culling of dairy cows. Part I. Effects of diseases on culling in Finnish Ayrshire cows. Prev Vet Med 41:195-208, 1999a.
23. Rajala PJ, Gröhn YT: Culling of dairy cows. Part II. Effects of diseases and reproductive performance on culling in Finnish Ayrshire cows. Prev Vet Med 41:279-294, 1999b.
24. Rajala PJ, Gröhn YT: Culling of dairy cows. Part III. Effects of 'disease, pregnancy, and milk yield on culling in Finnish Ayrshire cows. Prev Vet Med 41:295-309, 1999c.
25. Rajala PJ, Gröhn YT, McCulloch CE: Effect of milk fever, ketosis, and lameness on milk yield in dairy cows. J Dairy Sci 82: 288-294, 1999d.
26. Rajala PJ, Gröhn YT, McCulloch CE, Guard CL: Effect of clinical mastitis on milk yield in dairy cows. J Dairy Sci 82:1213-1220, 1999e.